Article

Geothermal site selection based on varying thermal parameters using the finite cylinder source method

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Academic Editor: name
Received: date; Accepted: date; Published: date

Abstract: Ground coupled heat pumps are recognized as a means of increasing energy efficiency and reducing emissions through geothermal energy. The purpose of this study was to demonstrate the influence site selection has on the feasibility and financial viability of geothermal projects. The impact thermal conductivity and volumetric heat capacity has on projects was investigated and a simplified costings was conducted based on total borehole length and number of required boreholes. The finite cylinder source method was used for modelling the borehole wall temperature and the ASHRAE method for sizing total borehole length. Thermal conductivity was found to have a much larger impact then volumetric heat capacity. Once thermal conductivity reaches 2 W/m K and volumetric heat capacity 2 x 10^6 J/m^3 K the increased heat transfer has significantly reduced the total borehole length by more than 30% when compared to 1 W/m K and 1 x 10^6 J/m^3 K respectively. Increasing past this point only had limited effectiveness. However, the savings generated was up to $32,800 from increasing thermal conductivity and only $8,500 from increasing volumetric heat capacity. This demonstrates the significant effect local ground conditions have on geothermal projects, larger thermal parameters, particularly thermal conductivity plays an important role.

Keywords: Geothermal borehole, thermal conductivity, volumetric heat capacity, finite cylinder source.

Nomenclature

Cp	Specific heat capacity (J/kg K)	R_{1m}	Ground thermal resistance, one month
$erfc$	Complementary error function	R_{10y}	Ground thermal resistance, ten years
H	Borehole length (m)	t	Time (s)
L	Total borehole length (m)	T	Temperature (K)
q	Heat flow input (W/m)	T_g	Undisturbed ground temperature (°C)
q_h	Peak hourly ground load (W)	T_m	Mean fluid temperature (°C)
q_m	Monthly ground load (W)	T_p	Temperature penalty (°C)
q_y	Yearly average ground load (W)	z	z-coordinate
r	Radius of pile/borehole (m)	*Greek symbols*	
r_0	Cylinder radius (m)	α	Thermal diffusivity (m²/s)
R_b	Borehole thermal resistance (m K/W)	λ	Thermal conductivity (W/m K)
R_{6h}	Ground thermal resistance, six hours	φ	Angular coordinate (rad)

1. Introduction

Sustainable and clean energy has been increasing rapidly in uptake around the world as technology advances reduce both the cost and increase efficiency. One of the sources of energy that has reaped the benefits of the push towards renewables is geothermal. The features of geothermal energy are what make it most appealing. Geothermal energy is considered a clean and sustainable source, capable of delivering a constant stream of energy with minimal emissions and reduced overall costs [1]. The main type of geothermal energy experiencing this boom is low-enthalpy energy used for heating and cooling purposes [2]. Low-enthalpy geothermal energy is typically sourced using ground coupled heat pumps (GCHP) as the means of transferring the energy into the structure or building. The GCHP utilizes geothermal boreholes for transferring energy to and from the surrounding ground. Each borehole consists of a U-loop buried in the ground and connected to the GCHP, a heat transferring fluid is circulated through this U-loop to exchange energy. Other configurations of the geothermal boreholes are used such as having an open or horizontal loop [3]. These configurations are determined on a case-by-case basis depending on local conditions. Although GCHP have long term benefits in reducing energy costs and emissions [4], their high up-front costs have meant that until recently there has been minimal penetration in energy markets [5]. However, rising energy prices and reduced costs have made them more competitive.

This study aims to clarify the large impact thermal parameters can have on a GCHP, highlighting the importance of site selection for any GCHP system. This will be done through modelling of borehole temperatures over time based on different thermal parameters, in addition to a simple expense calculation based on required borehole length and the number of boreholes.

2. Methods

The key thermal parameters when designing a shallow geothermal system are the thermal conductivity and the volumetric heat capacity (VHC). The thermal conductivity is a measure of a materials ability to transfer heat and is evaluated using Fourier's Law for heat conduction. Whereby VHC is a materials ability to store heat, or alternatively the amount of energy required to change the temperature. The VHC is obtained by multiplying the specific heat capacity by the density. These parameters are related using thermal diffusivity (Eq. 1).

$$\alpha = \frac{\lambda}{\rho c_p} \tag{1}$$

Recent research has focused on increasing efficiency by various means such as alternative fluids or configurations [6–8]. Obtaining optimal designs has been identified as an important measure in increasing efficiency, these designs have been tested through large-scale experiments to help give insights into the efficiency [9–11] . Where large-scale experimental work is not possible; modelling has been used to great effect, both numerical and analytical. However, often numerical modeling can be expensive and time consuming, in such cases analytical models are used instead. Analytical models require various assumptions to be implemented, to correctly capture the processes taking place, without at least some of these assumptions analytical methods would be too complicated to implement. These assumptions include:

1. The ground is infinite or semi-infinite.
2. The ground has uniform initial temperature.
3. The boundary condition for the wall of the borehole or heat transfer pipe is either constant flux or constant temperature.
4. Groundwater is either ignored or considered homogeneous.
5. The ground is treated as a medium with an equivalent thermal conductivity.

By far the most common analytical method is Kelvin's infinite line source method (ILS). Kelvin's ILS has a very clear physical definition; the heat source is taken as a single line with an infinite length. ILS method has proven extremely successful due to the ease of applying it to geothermal boreholes for a variety of configurations. The main shortcoming is that by assuming the length of the heat source is infinite the earlier behavior of the borehole is not accurately simulated and often the thermal parameters are overestimated as a result. To overcome these shortcomings an alternative method is used within this study, the finite cylinder source (FCS) method. Which is a combination of the infinite cylinder source (ICS) method and the finite line source (FLS) method.

The ICS gives the heat source (borehole) a defined radius [12], whereas the FLS uses a virtual heat sink to obtain a semi-infinite heat source [13]. Allowing the FCS method to define a radius and height for the geothermal borehole seeking to be simulated, resulting in higher accuracy at earlier time durations and more realistic assumptions overall [14], the FCS is shown in Eq (2) and (3).

$$r' = \frac{erfc\left(\sqrt{r^2 + r_0^2 - 2rr_0^2 \cos\varphi + \left(z - z_0\right)^2} \Big/ \sqrt{4\alpha t}\right)}{\pi\sqrt{r^2 + r_0^2 - 2rr_0^2 \cos\varphi + \left(z - z_0\right)^2}} \tag{2}$$

$$T\left(r, z, t\right) = \frac{q}{4\pi\lambda}\left\{\int_0^H \int_0^\pi r'\ d\varphi_r' dz' - \int_{-H}^0 \int_0^\pi r'\ d\varphi_r' dz'\right\} \tag{3}$$

Despite a surge in recent research, one aspect that cannot be enhanced is the ground conditions of any installation. GCHP have been shown to be versatile in almost any weather conditions and by far the largest impact on efficiency is not the GCHP or the heat carrying fluid, but the ground thermal parameters. This is a study of a typical geothermal borehole field using the finite cylinder source method (FCS) in conjunction with the ASHRAE method for borehole sizing [15].

The ASHRAE method was developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and is a simple means to determine an estimate of the required total borehole length based on ground conditions and the building energy requirements. There are several assumptions underpinning this method. These assumptions include that conduction is the only source of heat transfer in the ground and that the groundwater movements are not significant [16].

$$L = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{T_m - \left(T_g + T_p\right)} \tag{4}$$

Using both the FCS and the ASHRAE method for modelling purposes allows the temperature change over time of the borehole and surrounding soil to be simulated. This was conducted for a range of different thermal parameters. For this study the borehole dimensions simulated had a depth of 80 m with a width of 0.2 m (see **Figure 1**). The heating input was 6 kW, representing 75 W/m, within the recommended range of 40 W/m to 80 W/m [17].

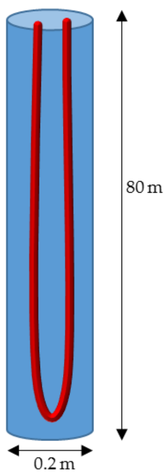

Figure 1. Layout of the borehole U-loop.

The thermal conductivity range being investigated was from 1 – 4 W/m K with increments of 1 W/m K, VHC was kept constant at 3.2 x 10^6 J/m^3 K when thermal conductivity varied. For investigation of the VHC, the range being evaluated was 1.0 x 10^6 – 4.0 x 10^6 J/m^3 K, with the thermal conductivity kept constant at 2 W/m K when VHC varied.

These values were chosen to represent realistic values commonly found in soils. A typically soil will have a thermal conductivity in the range of 1 W/m K to 3.5 W/m K. Whereby the VHC may be in the range 1 x 10^6 J/m^3 K to 4 x 10^6 J/m^3 K [18].

3. Results

3.1 Finite Cylinder Source Method Modelling

Figure 2 show the large impact increasing thermal conductivity can have on the temperature of the borehole wall over time. The trend is quite clear, the larger the thermal conductivity of the surrounding ground the lower the temperature increase over time. Thirty days have been simulated, typically 2 – 3 days of testing is undertaken to determine the thermal parameters, whereby an operational GCHP system would be expected to last in the order of decades. Thirty days was chosen as the steady-state trend can be clearly seen by this stage, additionally a balanced system could expect a period of this length for operation.

Though this is extremely simplified, as a system would experience both heat injection and heat extraction over a period of years, whereby only heat injection is modelled. Lower temperatures due to higher thermal conductivity is a result of the higher thermal conductivity values transferring heat faster. Therefore, the heat is transported further away from the borehole wall and the heat build-up associated with lower values is not encountered. When using a GCHP system the higher thermal conductivity would be more beneficial as often a concern for the system is the heat balance over time. More heat injection or heat extraction leads to an imbalance, which reduces the efficiency of the system. The larger thermal parameters results in much faster recovery, and a subsequent smaller imbalance.

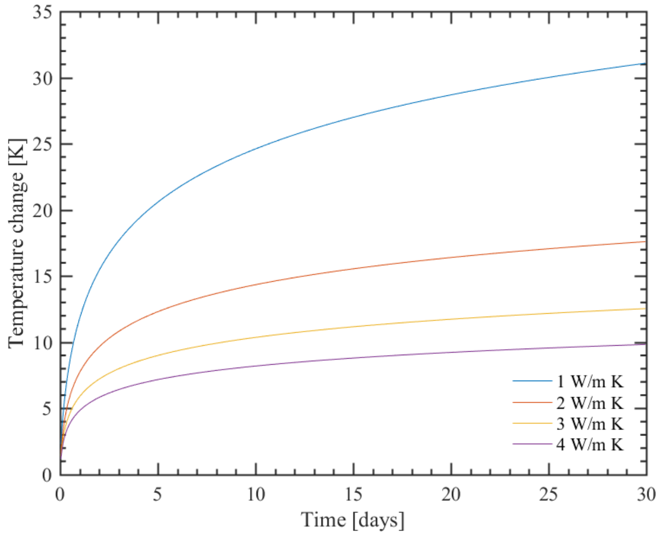

Figure 2. Temperature increase of borehole wall based on thermal conductivity

When using soils with different VHC values the associated temperature rise can be seen in **Figure 3**. Comparing the thermal conductivity response to the VHC response shows that thermal conductivity has a larger impact due to the markedly different temperature increases. Raising the thermal conductivity from 1 W/m K to 2 W/m K results in a temperature decrease of the borehole wall of approximately 13.3 K.

However, when increasing the VHC from 1 x 10^6 J/m^3 K to 2 x 10^6 J/m^3 K, a temperature decrease of approximately 2.1 K in experienced. It is important to note that the temperature decrease from an increasing of the thermal parameters experiences diminishing returns. Increasing the thermal conductivity from 3 W/m K to 4 W/m K only experiences a temperature decrease of approximately 1.9 K, a similar decrease is seen raising VHC from 3 x 10^6 J/m^3 K to 4 x 10^6 J/m^3 K. This demonstrates that the thermal conductivity has a much larger impact on the soil temperature then the volumetric heat capacity.

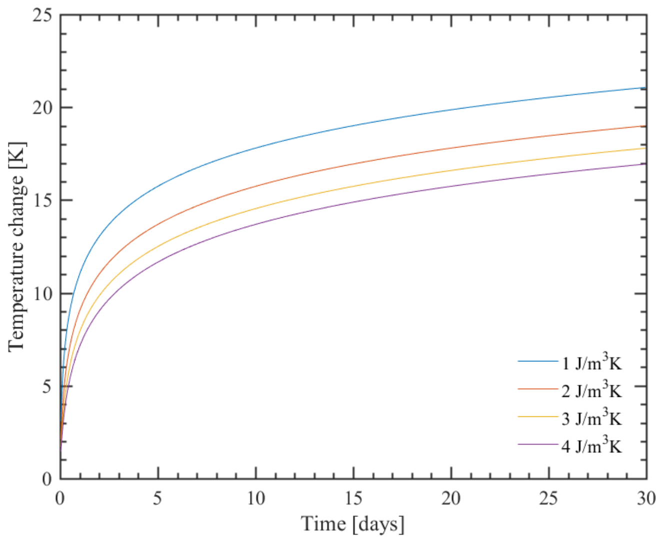

Figure 3. Temperature increase of borehole wall based on VHC

3.2 Required total borehole length

The same parameters used for simulating the temperature increase of the borehole wall were used for determining the total borehole length, using the load properties shown in **Table 1**. This is only an example load, depending on the size of the installation the values would change, and as a result, the estimated expenditure would change. Prior to construction of any structure, these load values should be obtained to evaluate the estimated running costs over the lifetime of the structure and the suitable of a geothermal installation.

Table 1. Load properties used determining total borehole length required

Ground loads	**(W)**
Peak hourly	200,000
Monthly	100,000
Yearly average	2,500

Further system parameters are required to estimate the total required borehole length (see **Table 2**). These parameters are site and installation specific and can vary significantly from each project depending on local conditions and the project requirements. The parameters selected are typical of a standard installation. The undisturbed ground temperature of 23°C was chosen based on the undisturbed ground temperature experienced in Brisbane, Australia, this undisturbed ground temperature is quite high. An example of a more moderate and lower temperature would be in Melbourne, Australia, where the undisturbed ground temperature is as low as 13°C [19]. The borefield aspect ratio is kept constant at 1 and the distance between each borehole is 8 m.

Table 2. Additional required parameter values

Parameters	
Fluid thermal heat capacity (J/kg K)	4200
Mass flow rate (kg/s)	0.5
Pipe inner radius (m)	0.020
Pipe outer radius (m)	0.019
Grout thermal conductivity (W/m K)	2.0
Pipe thermal conductivity (W/m K)	393
Center-to-center distance between pipes (m)	0.04

Table 3 displays the values obtained, whereby **Figure 4** compares the decreasing total length of borehole with the increasing thermal parameters. Clearly outlining the significant decrease experienced by increasing thermal conductivity when compared to the increasing VHC where a much more gradual decrease in borehole length is experienced. While having larger values for both of the main thermal parameters is important, the thermal conductivity should be of paramount concern during the initial stages of any GCHP project.

Table 3. Borehole characteristics based on thermal parameters

Thermal parameters	Total Borehole length (m)	Borehole length (m)	Number of boreholes
Thermal Conductivity (W/m K)			
1	1188	79.2	15
2	825	82.5	10
3	687	85.9	8
4	612	87.4	7
Volumetric heat capacity (x 10^6 J/kg^3 K)			
1	953	79.4	12
2	876	79.6	11
3	832	83.2	10
4	803	80.3	10

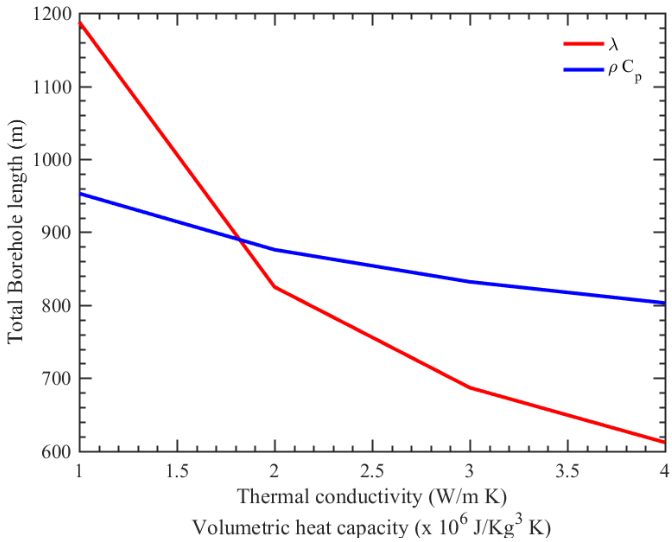

Figure 4. Comparison of the decrease length to increased thermal parameters

To simplify the estimated expenditure for the GCHP system there is an assumption of $50/m for drilling expenses [20] and an extra cost of $500 per borehole (manifolds, trenching and pipework). While these expense calculations are rudimentary, they offer insight into the large impact site selection can have on the feasibility of a project. For projects the drilling is considered the main expense, often it is more economical to have more borehole that are shallow then having less boreholes that are deeper. Drilling to deeper depths often can more time consuming and lead to a higher chance of complications. Both from a geotechnical perspective, such as encountering an unexpected rock strata and from a mechanical perspective, such as requiring a larger than expected compressor.

For this study when determining the borehole length the number of boreholes have been adjusted to ensure that the length for each borehole is as close to 80 m as is convenient, this length is considered quite standard, though the actual size resulting from the ASHRAE modelling ranges from 79.2 m to 87.4 m. When investigating the number of boreholes based on the thermal parameters it is shown that the decrease can be substantial, particularly for thermal conductivity whereby a 1 W/m K requires 15 boreholes, for the same system, a thermal conductivity of 4 W/m K only requires 7 boreholes (**Table 3**).

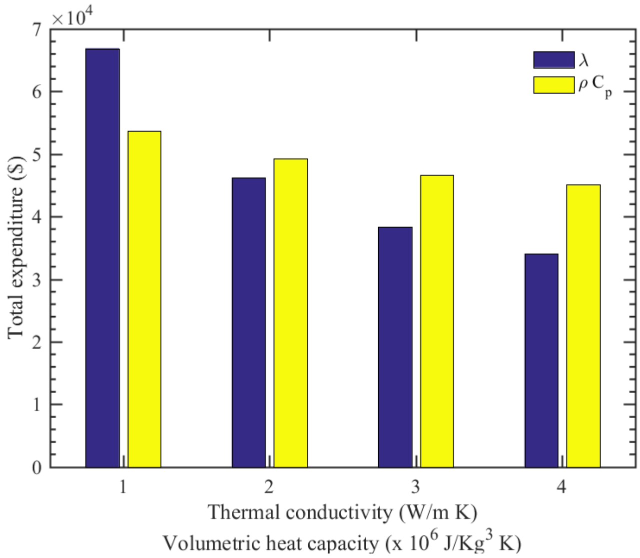

Figure 5. Total expenditure based thermal parameters

4. Discussion

When analyzing the economics of the boreholes the price difference between thermal conductivity values can be as much as 51%, however the major decline is experienced in the initial differences with a decline of 31% when the increase is from 1 W/m K to 2 W/m K. This shows that a site with a thermal conductivity of only 1 /m K would require a significantly larger investment to generate the same energy as a site with a thermal conductivity of 2 W/m K.

Furthermore, when compared to the VHC the decrease in costs is 16% across at the largest and less than 1% for the final increment (see **Table 4**). That the ground conditions can have such a large impact emphasizes the importance of choosing the appropriate site for any prospective GCHP installation.

Table 4. Estimated costsings for installation

Thermal parameters	Drilling ($)	Borehole ($)	Total ($)
Thermal Conductivity (W/m K)			
1	59,400	7,500	66,900
2	41,250	5,000	46,250
3	34,350	4,000	38,350
4	30,600	3,500	34,100
Volumetric heat capacity (x 10^6 J/kg^3 K)			
1	47,650	6,000	53,650
2	43,800	5,500	49,300
3	41,600	5,000	46,600
4	40,150	5,000	45,150

5. Conclusion

This study review several methods for modelling both the individual borehole and the borehole array. Provides a simplified costing to determine effect various thermal parameters can have on a geothermal project. The outcomes were such that the thermal conductivity is considered the main parameter to be taken into account at the initial stages of any geothermal project. Thermal conductivity has various influences the key component's include moisture content, minerology, in addition to volume fraction of both air and soils. As air is a poor thermal conductor, the higher the moisture content and volume fraction of soils, the larger the effective thermal conductivity.

GCHP installations are an increasingly popular means of achieving energy efficiency for buildings and reducing air-conditioning and heating costs. Ensuring that a comprehensive understanding of the impact site selection can have is essential, as reducing the financial burden is crucial for further advances in the technology.

Further research is considered necessary to determine additional design and installation improvements. Moreover, industry collaboration should be considered a key goal to ensure wide spread adoption of best practice techniques and raised awareness, both which are critical for further developmental goals.

Acknowledgments: The authors wish to acknowledge funding researched as part of the Australian Postgraduate Award from the Australian Federal Government in support of the research conducted by Scott H Lines.

Author Contributions: Scott H Lines designed the study, methodolody and wrote the initial draft manuscript, Marcelo Llano Serna performed a critical revision of the manuscript, David J Williams and Sergio Galindo-Torres reviewed and analysis the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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